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# Demonstration Apparatus To Illustrate the Operation Of Synchronous Machines

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# DEMONSTRATION APPARATUS
TO ILLUSTRATE THE
# OPERATION OF SYNCHRONOUS MACHINES

BY

KLAUS EDWARD HELLSTROM

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE
IN
ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING
UNIVERSITY OF ILLINOIS

PRESENTED JUNE 1908

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June 1, 1908

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

KLAUS EDWARD HELLSTROM

ENTITLED DEMONSTRATION APPARATUS TO ILLUSTRATE THE OPERATION OF SYNCHRONOUS MACHINES

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

Morgan Brooks
Instructor in Charge.

APPROVED: Morgan Brooks,

HEAD OF DEPARTMENT OF Electrical Engineering

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## INTRODUCTION

The circle diagram has recently been applied to the study of the interaction of synchronous machines by Professor Morgan Brooks and M. K. Akers, and it has served a useful purpose in the interpretation of the somewhat obscure problems involved in the operation of alternating current machines. The vector relations, which have been assumed in the application of the circle diagram, are known to be the least approximately correct,for oscillograph records have been found to closely approximate sine wave form. This justifies the theory that sucessive instantaneous values of electro-motive force and current follow one another in a manner strictly harmonic. Furthermore the assumption of constant impedance of the motor armature is entirely justifiable, in that it makes the study of the problem amenable to simple mathematical analysis.

In order to simplify the representation of the machine operation, an imaginary snap-shot is taken, as it were, of the vectors which represent by their lengths the effective electro-motive forces, and by their periods the respective frequencies of the two machines in question. One of these vectors is always taken in its vertical position, and the other will assume an angular position with the first, which depends upon the conditions existing. The theory of the circle diagram, and the consequent mathematical derivations and calculations need not be brought out here, except to clear up some points in the application of the demonstration apparatus. (Note: For a full discussion of the circle diagram theory

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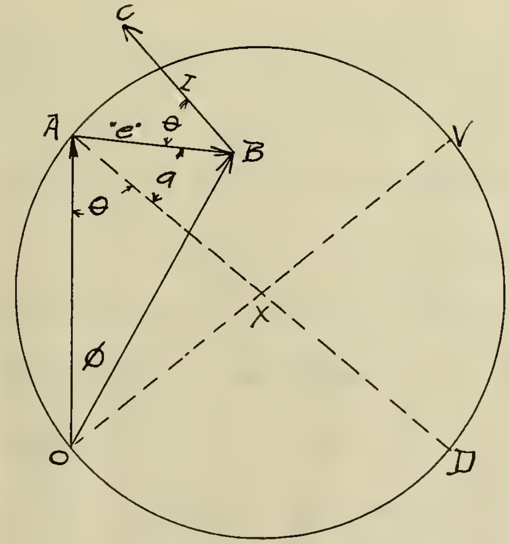
as applied to synchronous operation, refer to the Proceedings of the American Institute of Electrical Engineers for July, 1907, which contains the paper on this subject by Professor Brooks and Mr. Akers).

The primary object of this work is the design and construction of a simple piece of apparatus, which can be readily employed to illustrate in the class room the interaction of two single phase synchronoue machines, when operated in parallel, or as generator and motor. The apparatus must be of comparatively light weight, durable, and at the same time must be so constructed mechanically, that the vector electro-motive force and current relations can be demonstrated for various conditions of operation, and for various fixed conditions in the local machine circuit.



Fiqure 1

In Figure 1;

OA, or briefly A, represents the effective electro-motive force at the generator terminals. It is always taken in a vertical position, and will be assumed constant: this is secured by proper adjustment of the generator field.

OB, or briefly B, is the vector representing on the same scale the effective motor electro-motive force, which is variable in length and angular position.

$\phi$ is the angle between OA and OB, which depends for its value upon the relative excitation of the two machines, and the impedance of the motor and connecting lines.

AB, is the resultant electro-motive force due to the vector difference of OA and OB, which causes a transfer of power from machine A, acting as a generator, to drive machine B, acting as a motor.

This electro-motive force, AB, causes a current, CB, to flow in the circuit formed by the two armatures. This current, briefly I, has a definite relation to the electro-motive force, AB, (briefly e), for it is equal to "e" divided by the impedance of the motor armature plus the impedance of the line connecting the two machines. Since the value of impedance is assumed to be constant, the current I, varies directly with "e".

The phase angle, $\phi$, between the vectors OA and OB, is determined by the length of the vector "e", required to drive the current corresponding to the power demanded by the motor. The angle $\theta$, between the current, I, and the electro-motive force "e", depends

for its value upon the resistance and impedance of one machine armature and the connecting line. It is equal to the $\cos^{-1}\frac{R}{Z}$, when R, is the resistance, and Z, is the impedance, both of which are assumed constant. Cos $\theta$ is the true power factor of the circuit, and EI, cos $\theta$, represents the power transferred at any instant from the generator, A, to the motor B. In order to demonstrate the parallel operation, which includes the case of generator and motor action, under all conditions, the apparatus must be so constructed as to allow the following:- OA, must be fixed in position and length. OB must be pivoted at O, and must be adjustable in length and angular position. The vector AB, must always pass thru the point A, and also must be connected to the extreme point of the vector OB, and the current vector CB, must always have a length proportional to the distance AB, and must at the same time make a fixed angle, $\theta$, with AB.

## DESCRIPTION OF APPARATUS.

The apparatus is designed to demonstrate the interaction under two conditions, which differ considerably. These conditions are governed by the true circuit power factor, or the cosine of the angle between the resultant electro-motive force and the circulating current in each case. In the one case, the power factor of the circuit is assumed at .342, making the angle $\theta = 70^\circ$, and in the other case it is taken at .707, making the angle equal to $45^\circ$. These two angles may be taken as approximately the limiting values of operation, and hence are well chosen for demonstrating purposes.

The vector OA, is taken equal to 20 inches in each case, thus allowing its adaption to some scale, which may be used in determining true values of the other electro-motive forces and current values under various conditions.

The working drawings of the machine parts of the apparatus, shown on the following pages, indicate how the relation motion of the vectors AB and BC, is secured, and also how the constant angle $\theta$, is maintained in each case. Figure 2 is drawn to scale to represent the construction of the brass box which controls the vector motion in Case 1, where $\theta$, is $70^\circ$, and Figure 3 represents the box construction for Case 2, $\theta = 45^\circ$. In each case the box is pivoted upon a pin, which is inserted in the brass bearing shown in Figure 4, and two washers are employed to take up the motion. Figures 6 and 7, show the brass pinions and racks, of 32 pitch, by means of which the relation vector motion is secured. In Figure 10 is shown the box of Figure 2 assembled and mounted upon the board used to support the vectors. The pinions upon which the racks run are rigidly fastened to the roller, which is free to rotate about a vertical axis, thus moving one rack an amount equal to the other. Figure 8 represents the collapsible tubing, 3/16" in diametre which is used as the movable vector, and Figures 5 and 9, indicate the manner in which the ends of this vector are made fast in their respective positions.

Figure 11, is drawn to scale to represent one side of the apparatus complete for which the angle is 70°. The box is supportad upon a square piece of rubble-board, 48" by 48", upon both sides of which are glued coverings of heavy canvas cloth, to give strength and to permit the drawing of certain loci, necessary to the demonstration. The edges of the board are protected by a metal band as shown. The vector OA, is drawn in black india ink, 20" in length, and a circle is laid out whose diameter is $20/\cos 70 = 20/.342 = 58.5''$. This makes OA a chord of the circle, and gives the desired angle of $\theta = 70°$. The bearings, shown in Figure 4, are inserted in the board at the points O and A, thus permitting the box of Figure 2, to be used upon one side at A, to demonstrate Case 1, and also permitting the box of Figure 3, to be used upon the reverse side of the board at O, to demonstrate Case 2.

In each case the vector OA, is maintained 20" in length, and the points O and A, are interchangeable to facilitate the construction, as well as the operation of changing from one case to the other. Each box is so designed that it revolves upon an axis in the circumference of the circle, which passes thru the intersection of the vectors AB and BC. The method of connecting the movable vectors, and their relations, are evident from the figure. The vector AC, is the uppermost one, and hence does not interfere with the movement of the point B, to any desired point upon the board. This construction makes it necessary to have the current vector located at A, instead of at B, where it should properly be, but this is in no way undesirable as it does not hamper the clear conception

of the existing conditions.

Figure 12 shows the reverse side of the board, designed to represent Case 2, and it differs in the value of the phase angle θ, and hence in the size of the reference circle, since the same length of vector is employed. The diameter of the circle in this case is $20/\cos 45^{\circ} = 20/.707 = 28.3''$, and this makes OA a chord, and gives the required angle, $\theta = 45^{\circ}$. It is now evident that in either case, the vector OA is fixed in position and length, OB, is pivoted at O, and is adjustable in length and angular position; AB always passes thru the point A, and is always attached to the extreme point of OB, and the current vector, CB, always has a length proportional to the distance AB, and at the same time, makes a fixed angle, θ, with AB, so all the desired conditions are secured. When OB is shortened, and moved over so as to lead OA, it represents a generator action, and OA, becomes the motor, and the current is reversed as it should, indicating a transfer of power now from machine B, to machine A.

In the figures representing the complete apparatus, three sets of more important loci are shown, and their significance will be brought out. These loci, altho simple curves, may be mathematically derived by means of the circle diagram theory, and their application to the machine operation is of more than mere theoretical value.

(a) Let P' designate the power output of the generator. The expression for power output in terms of other known factors is derived:- $P' = AC/Z \cos a$, when "a" is the angle shown between the

lines AB, and AC. From this equation it is evident that for constant P', e cos a, the projection of "e" on the line AC, is constant, or the locus of B, lies in a line perpendicular to AC, since A and Z, are constants. Thus the power output of the generator is directly proportional to the length of the projection on AC, and may be directly measured by the length of this projection. The lines drawn in brown ink, therefore, represent loci of the point B, for various constant values of P'. The line tangent to the reference circle at A, illustrates the case of P' = 0, and the parallels to the right, for the position values of P', show generator action, while those to the left, for negative values of P', show the motor action of machine A.

(b) The efficiency loci of the point B, are determined from the equation:- $A/\cos\theta\,(1-P''/P') = E/\cos a$, where P" is the power intake of the motor. For any given value of efficiency, P"/P', the first member of the equation becomes constant, and the equation is the polar equation of the circle. Hence for different efficiencies, circles of different diameters are formed, but all pass thru the common point A. They are shown in red ink upon the diagrams:-

for 100% effeciency , the locus of B is the point A.

for .9% effeciency, the locus of B lies in a circle whose diameter is .1A/cos a.

for .5% effeciency, the locus of B lies in a circle whose diameter is 5A/cos a.

The locus for 0% effeciency, coincides with the reference circle, which is also the locus of zero intake of machine B.

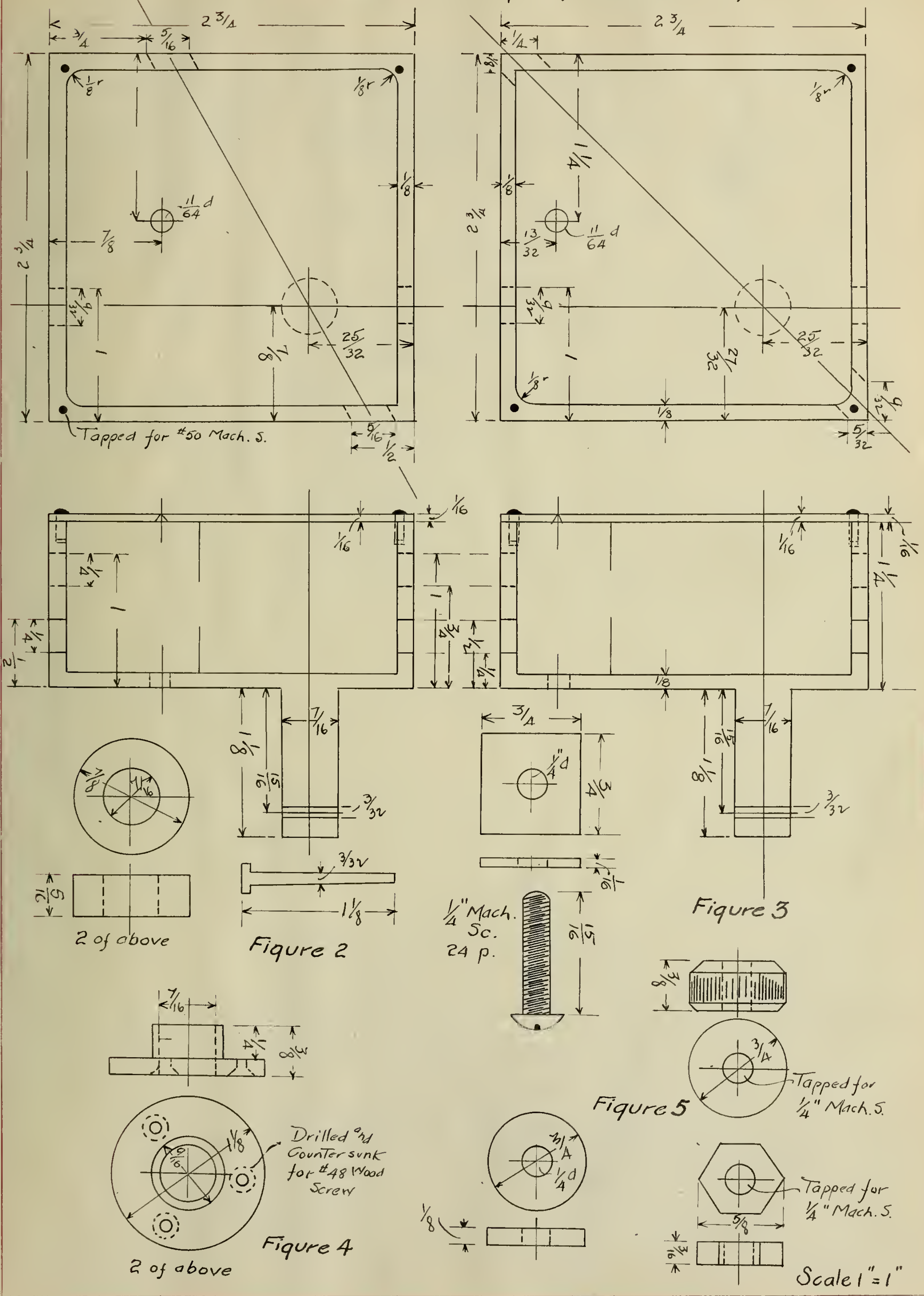
(c) The semi-circles drawn in blue, represent loci of the point B, for constant values of power intake to the motor, and they are derived from considerations of effeciency and power output of the generator in each case. At the points where an effeciency circle cuts the line of constant generator output, such as M, Figure 11, the value of P", the motor intake, is equal to the generator output of that locus, multiplied by the effeciency represented by the cutting locus, and the locus of constant P", is a circle, with a center at C, and a radius CM. In a similar manner, the other loci of the constant P" are derived.

The line indicated upon the reference circle as making a angle of 39° with the vector OA, is the position OB, which will cause practically full-load current to flow in the two machines. This relation is secured for the reason that synchronous machines are so designed as to allow full load current to flow on the application of a voltage equal to one third of the normal machine voltage, or A/3. Since the two machines are in series, two thirds of the normal voltage of one machine is required, and this is the value of the electro-motive force, AB, will assume, when OB, makes an angle of 39° with OA.

A number of synchronous machines may be operated together, some as generators, and some as motors, and the machines may vary greatly in size. But for the purpose of this demonstration two exactly similar single phase synchronous machines have been used,

and the clear conception of their simple action may be a considerable aid in understanding more complicated problems. If this apparatus helps to accomplish that purpose, it is well worth while.

# Working Drawings of Machine Parts #1 (all brass)



Scale 1" = 1"

# Machine Parts #2. (all brass)

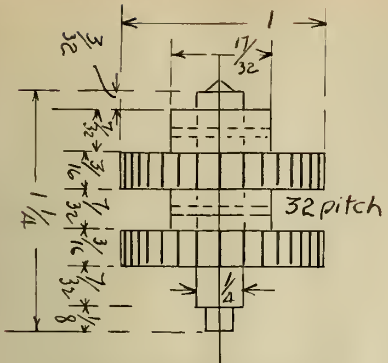


Figure 6

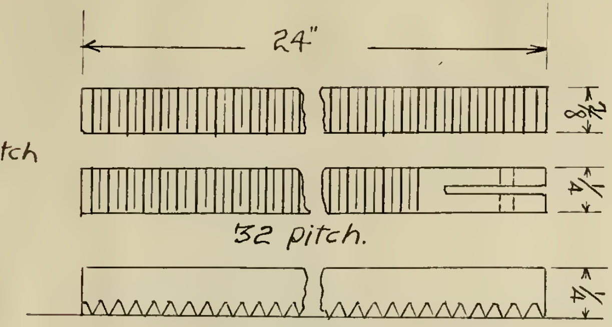
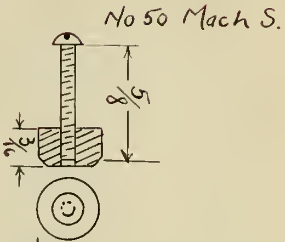


Figure 7



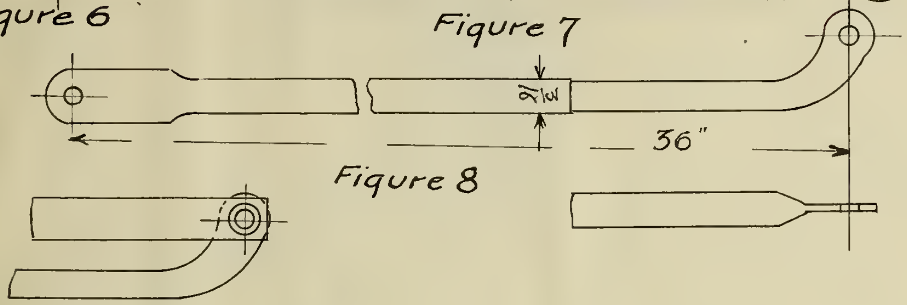
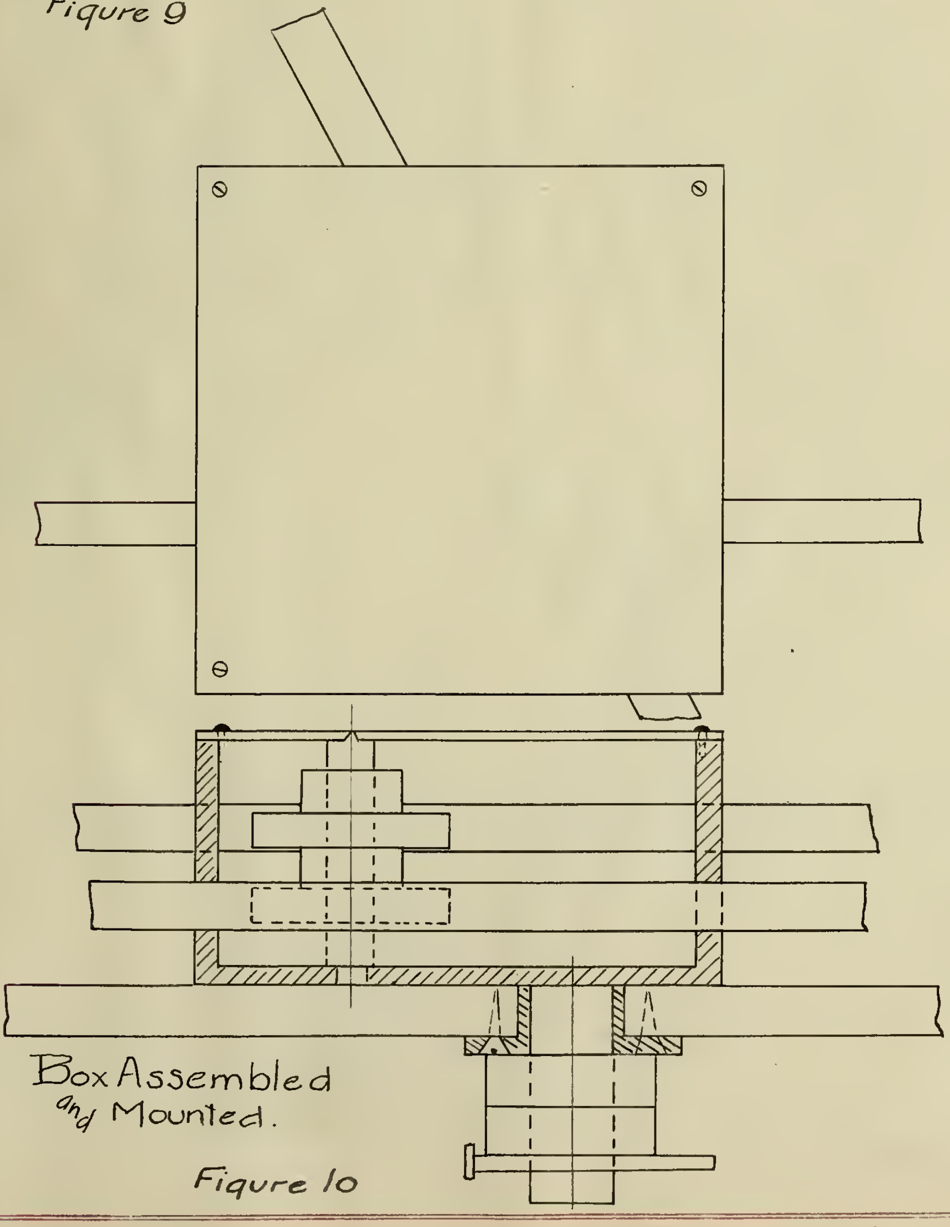


Figure 8

Figure 9



Box Assembled and Mounted.

Figure 10

# Apparatus Complete
## Side One - θ = 70°

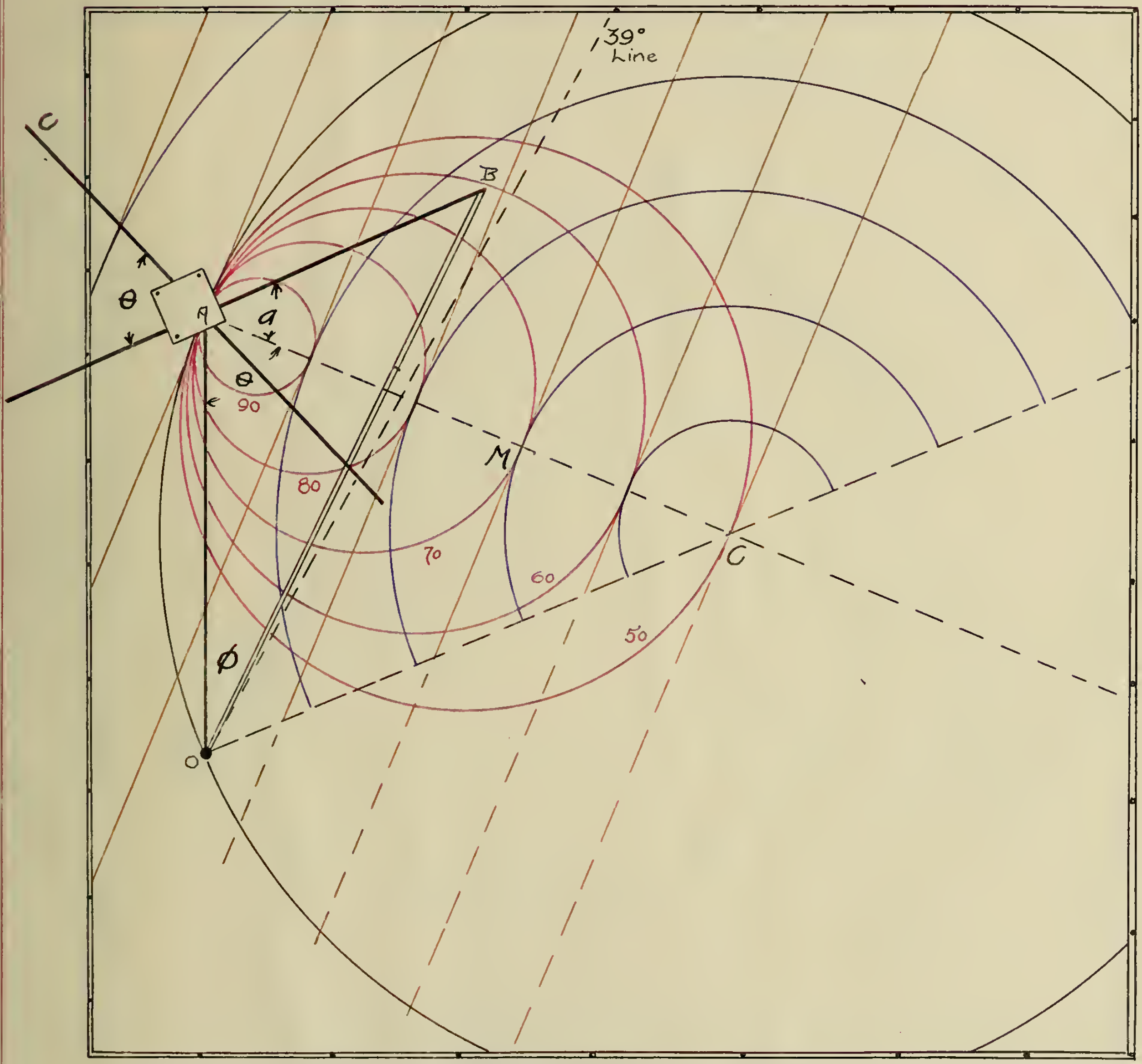


Figure 11.

Scale 1" = 8"

# Apparatus Complete
## Side Two - $\theta = 45°$

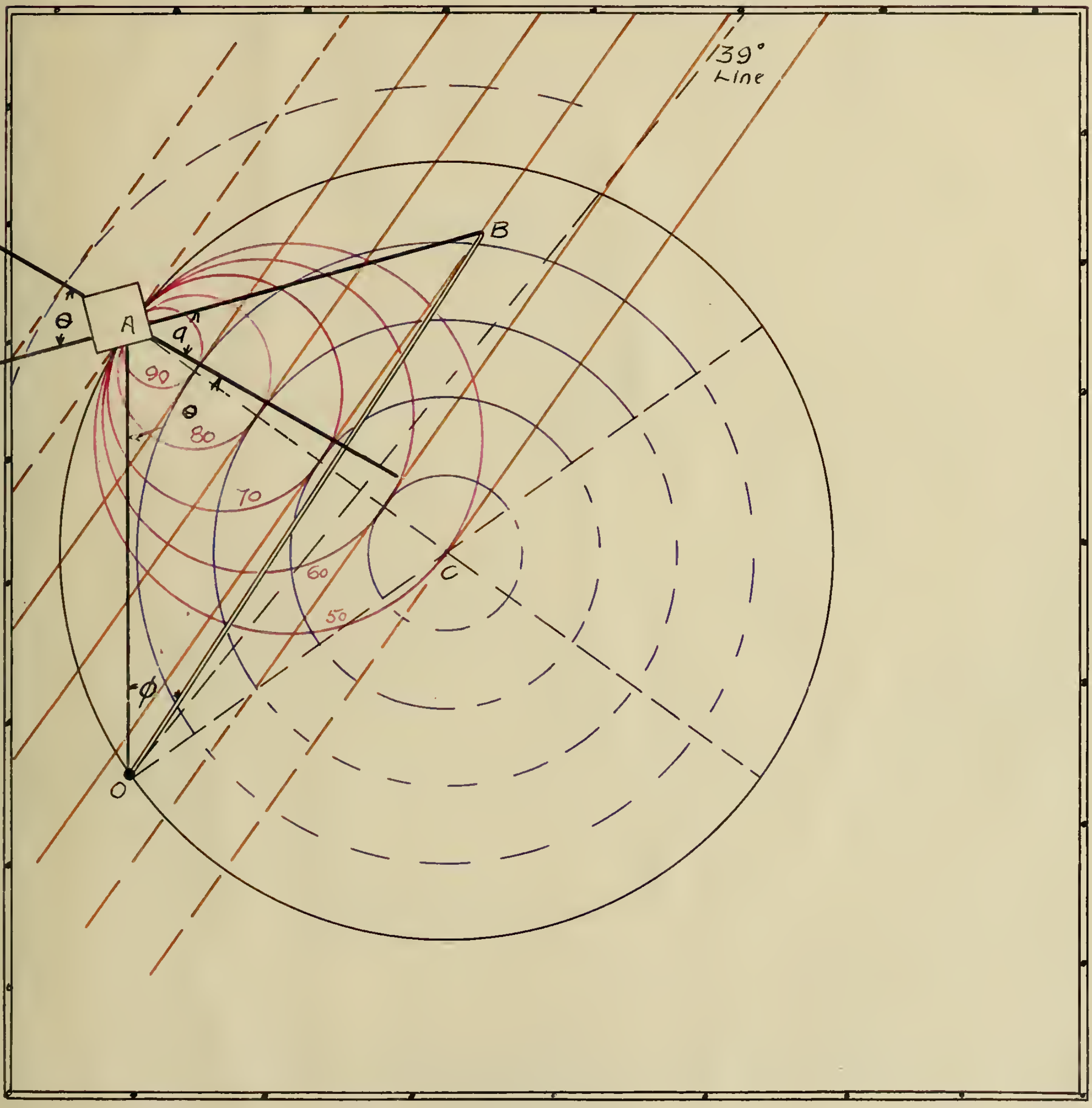


Figure 12.

Scale 1" = 8".

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